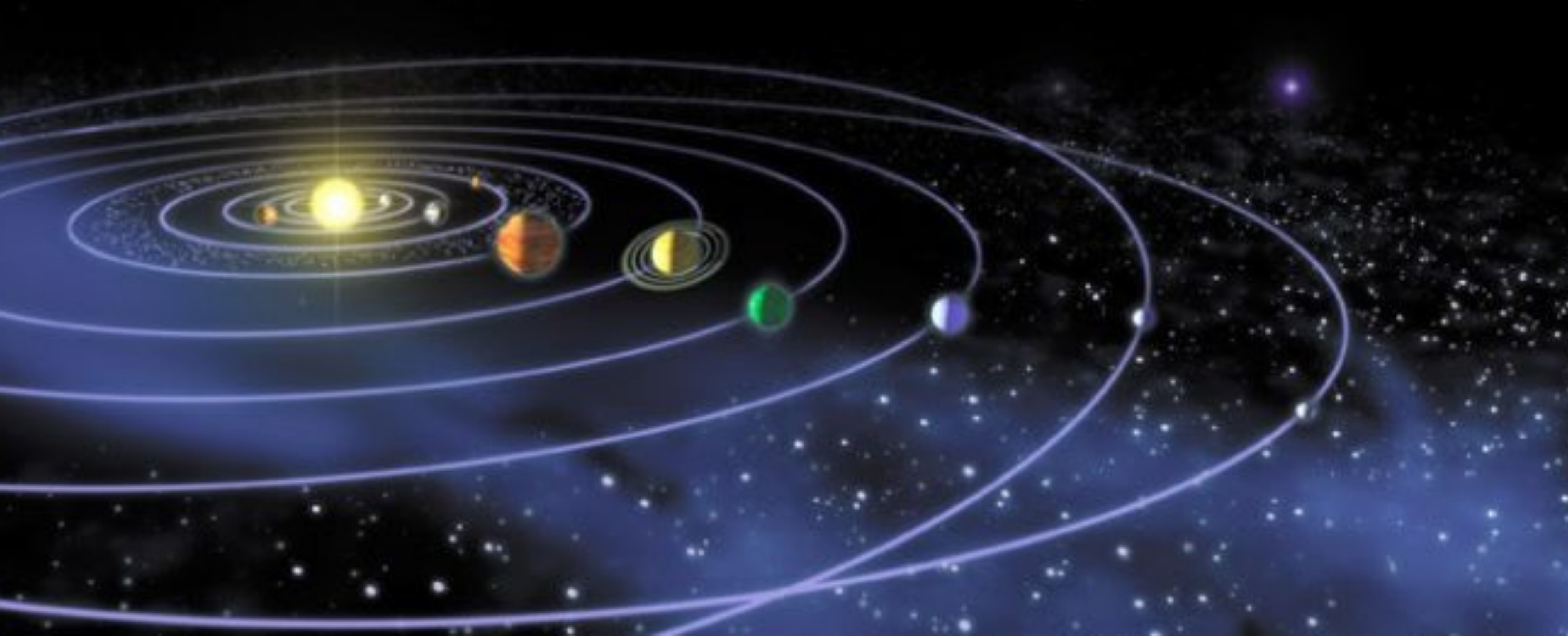

Kilopower–Nuclear Electric Propulsion for Outer Solar System Exploration

A Study for the NASA Space Technology Mission Directorate by

Glenn Research Center, Jet Propulsion Laboratory, and Los Alamos National Laboratory

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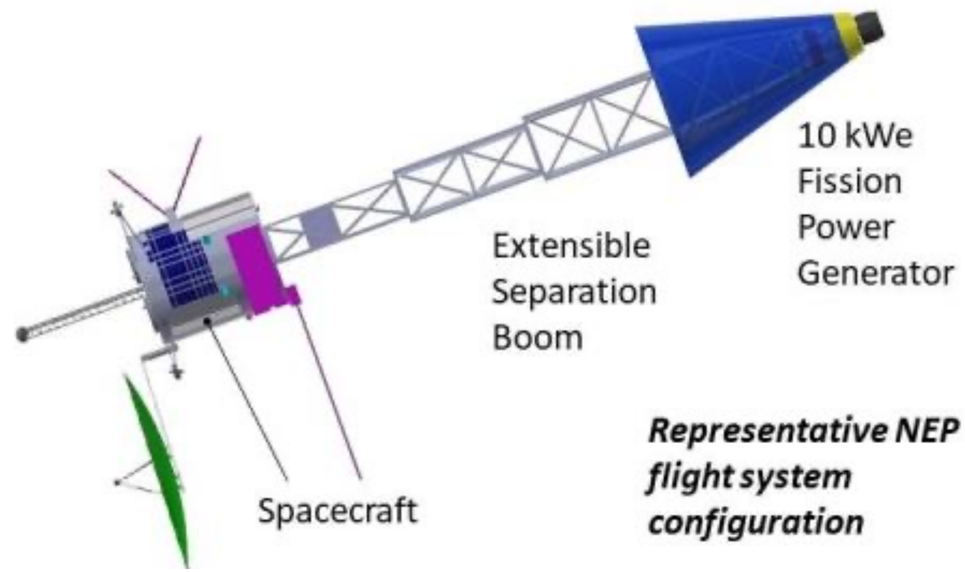
The work presented in this report was a collaborative effort carried out at Los Alamos National Laboratory (LANL), Glenn Research Center (GRC), and the Jet Propulsion Laboratory, California Institute of Technology (JPL), and was sponsored by Department of Energy and the National Aeronautics and Space Administration. The content of this report is pre-decisional information and is provided for planning and discussion purposes only.

Purpose of Study

- The study objective was to identify generic and specific benefits of using conceptual NEP systems for outer solar system exploration.
- Two classes of missions were studied:
  - **Enabled:** Missions that are not possible using any other available power and propulsion system.
  - **Enhanced:** Mission types using four example destinations studied previously by COMPASS or Team-X to show quantitatively the improvement possible with NEP.



Representative NEP flight system configuration

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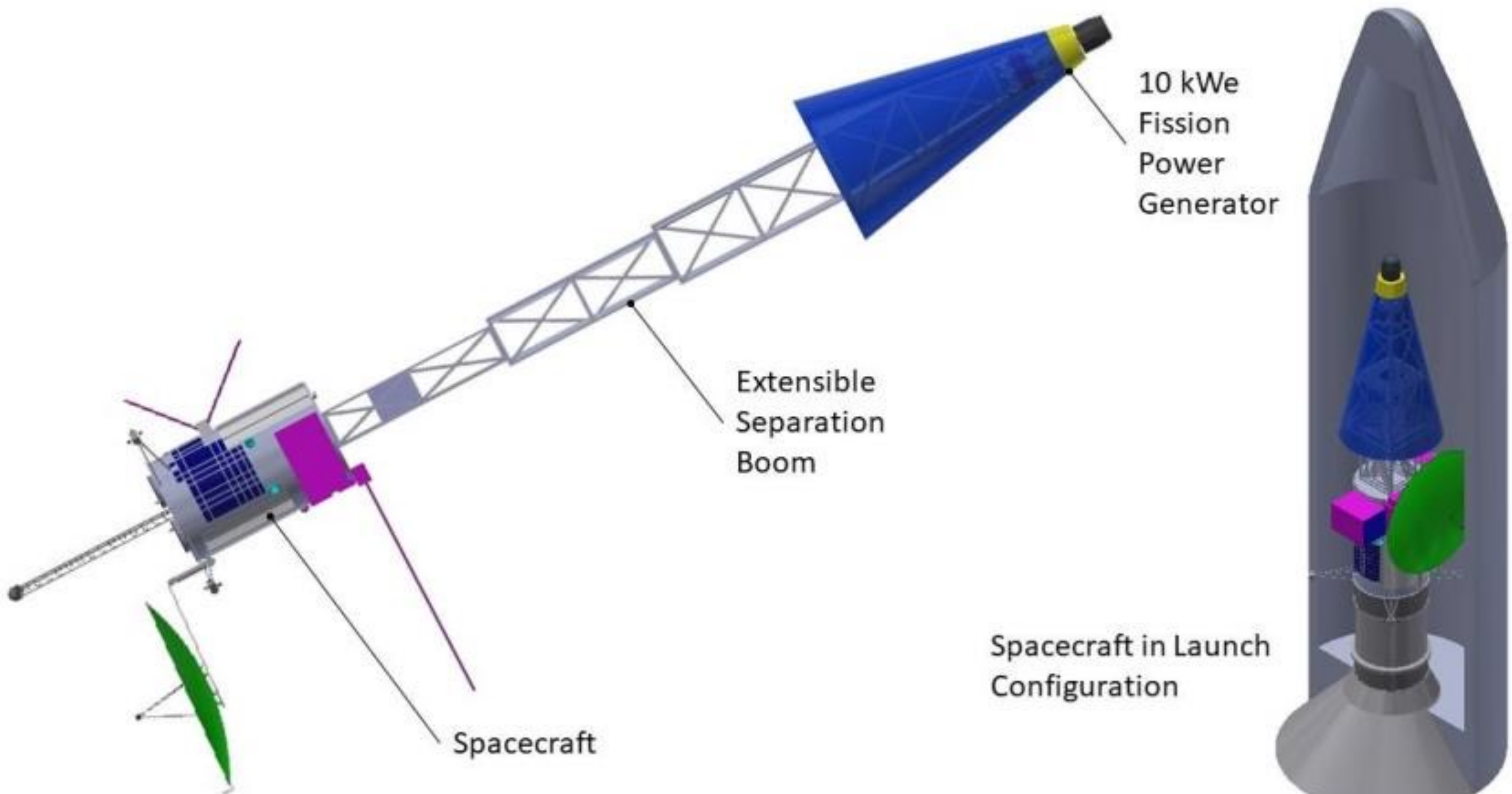
Notional Flight System Configuration



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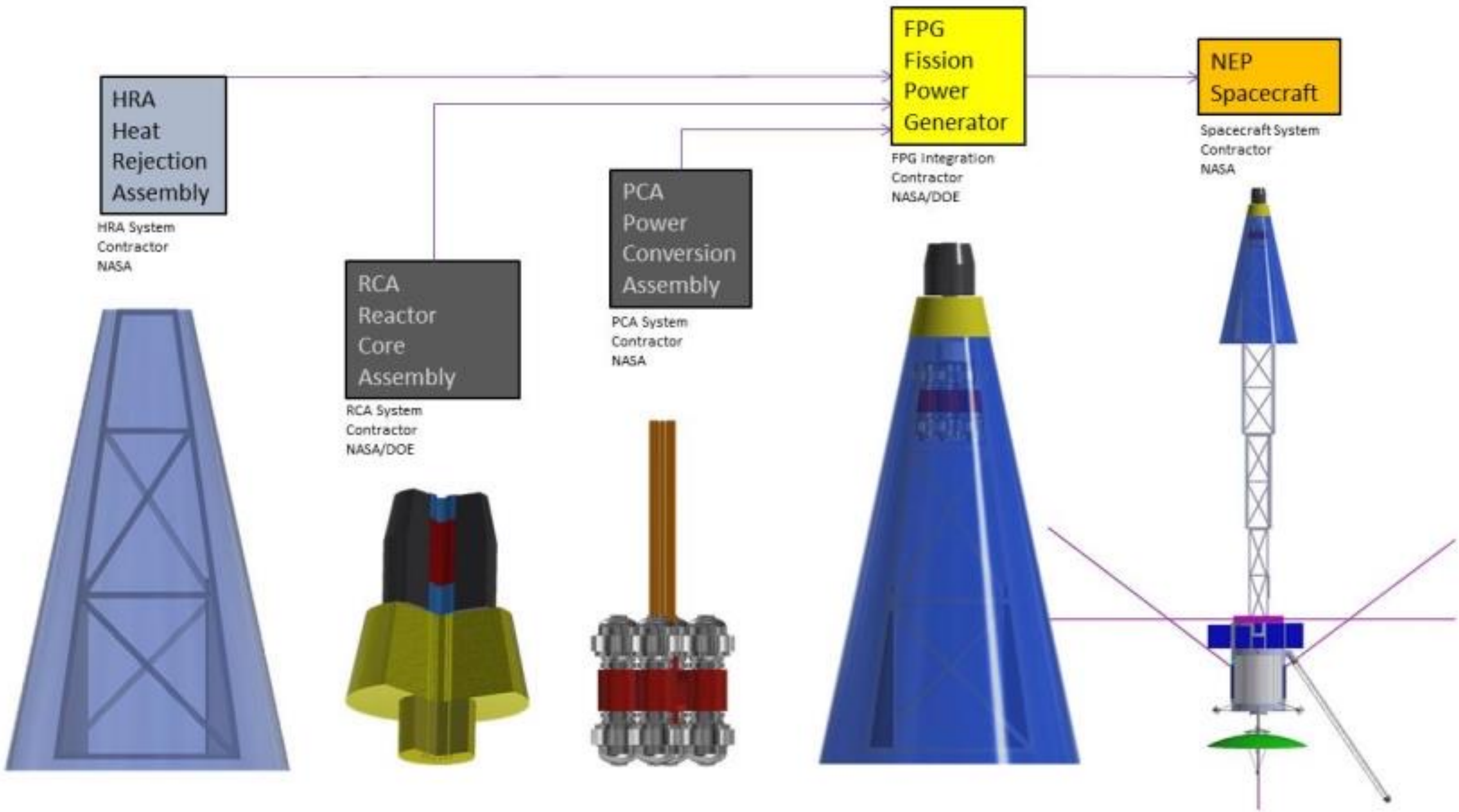
Fission Power Generator

(Baseline Design)



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NEP Benefits Outer Solar System Exploration

- ΔV requirements for outer solar system missions present a major challenge to chemical propulsion systems.
  - New Horizons flew by Pluto at 14 km/s, well beyond the ability of any existing chemical propulsion system to achieve orbit insertion.
  - As an example, imparting 10 km/s to a vehicle with 400 kg dry mass (New Horizons–class) using a conventional bi-prop system (Isp~320s) would require 9,300 kg of propellant, clearly not possible with a 400 kg dry mass.
  - Accounting for the tankage and structure mass for the propellant, would require more than 40,000 kg of wet mass.
- Electric propulsion provides fuel efficiency to achieve high ΔV
  - Imparting the same 10 km/s to the same 400 kg dry mass vehicle using EP ion thrusters operating at an Isp of 4000 s would require just over 100 kg of propellant.
- Nuclear power is enabling for missions to the far Outer Solar System
  - Solar power is currently not practical at large solar ranges (beyond Saturn).
  - Advanced radioisotope power (~1 kWe) could be used to enable small spacecraft missions with limited payloads (New Horizons–class).
  - Fission power (~10 kWe) could enable flagship-class missions at large solar ranges, including multi-body orbiters, large payload suites, and landers.

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Titan/Enceladus Mission Concept Enabled

A mission that could orbit Enceladus and then Titan, and deliver landers to both

- Falcon Heavy class launch vehicle
- Launch mass 9442 kg
- 9.75 years to Saturn with cruise science
- 2.25-year tour of icy moons with remote sensing science
- 0.5-year Enceladus orbit with remote sensing science + one or more landers
- 2-year tour to Titan with science + one or more landers
- 0.5-year Titan orbit with science
- Total science payload mass = 2550 kg (e.g., multiple Titan and Enceladus landers)

ΔV and spacecraft mass at different stages of the Saturn mission	
Event	Mass After Event
Launch, C3 = 22.66 km^2/s^2	9442 kg
Interplanetary ΔV to Saturn, 7.0 km/s	7903 kg
ΔV to Enceladus & Enceladus Ops, 1.5 km/s	7607 kg
ΔV to Titan & Titan Ops, 2.0 km/s	7229 kg

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Neptune/Triton Mission Concept Enabled

Enough performance to orbit Neptune and Triton and deliver a lander

- Falcon Heavy class launch vehicle
- Launch mass 6716 kg
- 13 years to Neptune with cruise science
- 1.4-year Neptune tour with 100 kg of orbiter science
- 0.6-year Triton orbit with 100 kg of science
- 300-kg dry mass Triton lander and lander ops
- Total science payload mass = 400 kg

ΔV and spacecraft mass at different stages of the Neptune mission	
Event	**Mass After Event**
Launch, C3 = 34.93 km^2/s^2	6716 kg
Interplanetary ΔV to Neptune, 20.2 km/s	4006 kg
Neptune orbit Insertion, 240 m/s (chemical)	3713 kg
Tour ΔV to Triton orbit, 2.1 km/s	3520 kg

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Dual Centaur Orbiter Mission Concept Enabled

With enough ΔV capability to orbit two Centaurs (including Chiron)

- Falcon Heavy class launch vehicle
- Launch mass 5290 kg
- 6 years to rendezvous with 2007 SA24
- 1-year orbital mission at 2007 SA24
- 4.5 years to Chiron rendezvous
- 3.5-year orbital mission
- Total science payload mass = 300 kg instrument
- Other Centaur pairings possible

ΔV and spacecraft mass at different stages of the dual Centaur mission	
Event	Mass After Event
Launch, C3 = 49.84 km^2/s^2	5290 kg
Interplanetary ΔV to 2007 SA24, 10.42 km/s	4057 kg
Orbiting 2007 SA24 ΔV, 0.250 km/s	4032 kg
Interplanetary ΔV to Chiron, 10.22 km/s	3108 kg
Orbiting Chiron ΔV, 0.250 km/s	3088 kg

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Saturn & Uranus Mission Concepts Enhanced

- When compared to REP, NEP has the potential to reduce trip time, increase data rates, and massively increase the payload capability of a single mission.
- Performance benefits could lead to a dramatic increase in the scientific return of a mission by returning more data in less time and carrying more capable science payloads.
- The maximum payload mass is above that which is required for the spacecraft and could be allocated to science instruments, atmospheric probes, landers, or additional propellant.

Comparison of REP and NEP orbiter missions to Saturn and Uranus

Mission	Figure of Merit	1-kW REP	10-kW NEP
Saturn Orbiter	Minimum TOF (Years)*	5.0	4.8
	TOF for Maximum Payload Mass (years)	13.0	12.6
	Maximum Payload Mass (kg)	1,095	7,840
	Communications Data Rate (kpbs)	120	530
Uranus Orbiter	Minimum TOF (years)*	11.7	10.2
	TOF for Maximum Payload Mass (Years)	14	14
	Maximum Payload Mass (kg)	175	3,320
	Communications Data Rate (kpbs)	30	130

* to deliver a minimum science payload mass of 30 kg for REP or 50 kg for NEP

Neptune & Pluto Missions Concepts Enhanced

- With NEP, the trajectory for a Neptune orbiter could deliver 875 kg to Neptune orbit for instruments and atmospheric probes. A 1-kW REP mission could deliver only 30 kg and would require 15 years.
- For the Pluto orbiter, an NEP spacecraft can deliver 67% more payload with 2.4 years shorter flight time (14.7 years) compared to REP option. Kilopower also enables >4× the data rate at Pluto than the REP option.

Comparison of REP and NEP orbiter missions to Neptune and Pluto

Mission	Figure of Merit	1-kW REP	10- kW NEP
Neptune Orbiter	TOF (years)	15	13
	Science Payload (kg)	30	875
	Communications Data Rate (kpbs)	13	54
	Flyby Sequence	Jupiter	Earth, Jupiter
	Launch Vehicle	Delta IV H + Star 63	Falcon Heavy
Pluto Orbiter	TOF (years)	17.1	14.7
	Science Payload (kg)	30	50
	Communications Data Rate (kpbs)	7	30
	Flyby Sequence	Jupiter	Earth, Jupiter
	Launch Vehicle	Delta IV H + Star 63	Falcon Heavy

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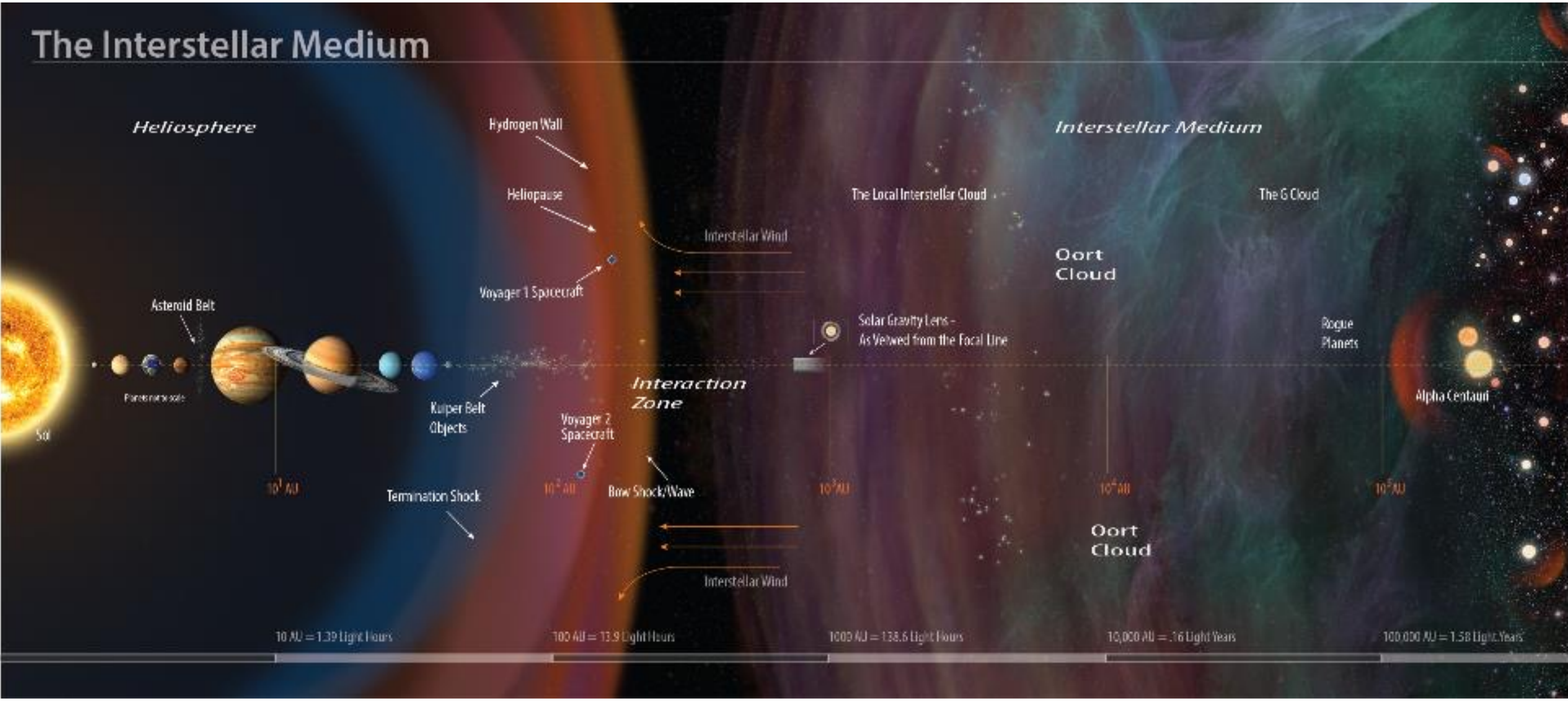
Interstellar Medium (ISM) Mission Concepts



- 2013/2014 KISS Workshop Led by E. Stone, L. Alkalai explored ISM missions and needed technologies. Was followed by studies at JPL, MSFC, and APL.
- JPL concept used a low perihelion with Solar Thermal Propulsion (STP) and NEP to achieve high escape speeds.

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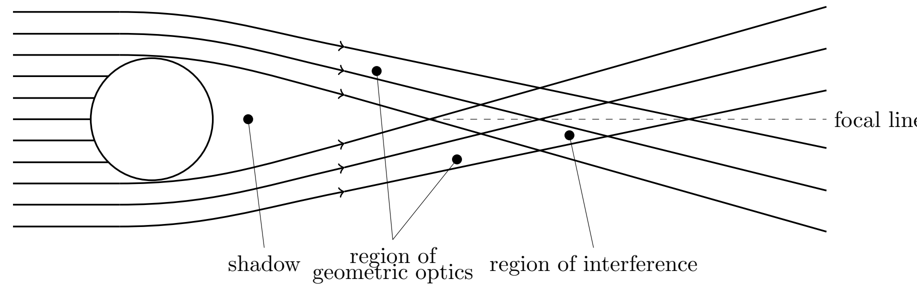
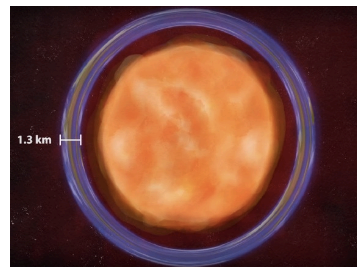
Solar Gravity Lens Focus

- Starting at ~600 AU, the Sun's gravity could be used as a lens to image exoplanets.*
- The focal line extends to infinity and the spacecraft could move about the line to image all exoplanets in a star system.
- The image would be constructed for each exoplanet by deconvolving multiple Einstein rings imaged over 6-12 months from different locations along the focal line.
- The resulting image could be up to 10 km/pixel resolution (for an exoplanet 30 parsecs away).





* Turyshev et al. "Direct Multipixel Imaging and Spectroscopy of an Exoplanet with a Solar Gravity Lens Mission," Final Report for the NASA's Innovative Advanced Concepts (NIAC) Phase I

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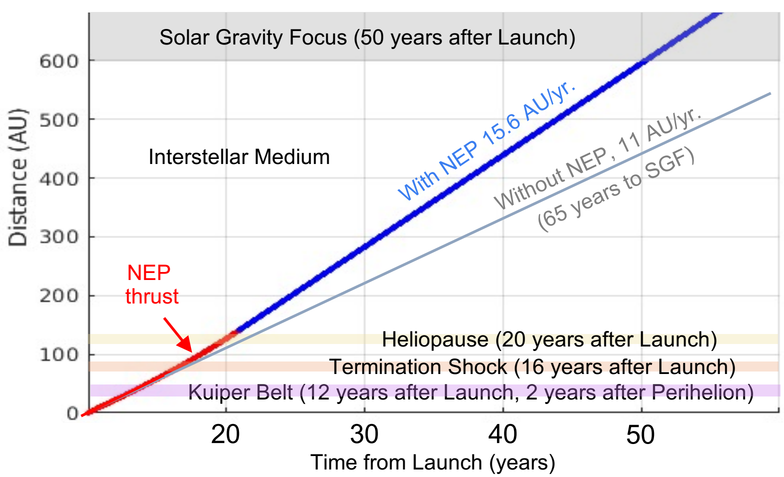
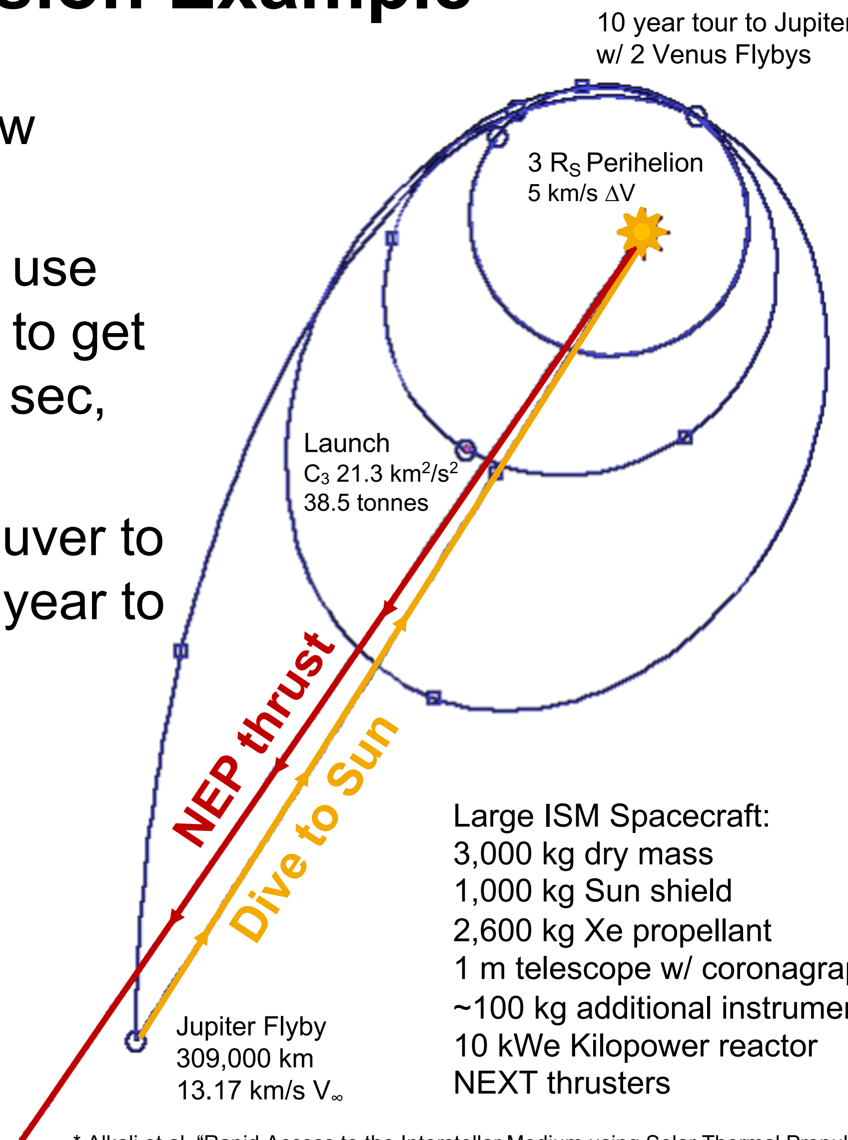
ISM / SGLF Mission Example

- A Jupiter flyby (with a 6.3 yr. tour, SLS launch) would be used to get a very low perihelion (3 R_S).*
- Solar Thermal Propulsion (STP) could use Hydrogen from cooling the heat shield to get very high specific impulse (1077-1283 sec, depending on Solar distance)
- STP would be used for a 5 km/s maneuver to get an escape speed of 11 AU/yr. (< 1 year to Saturn).

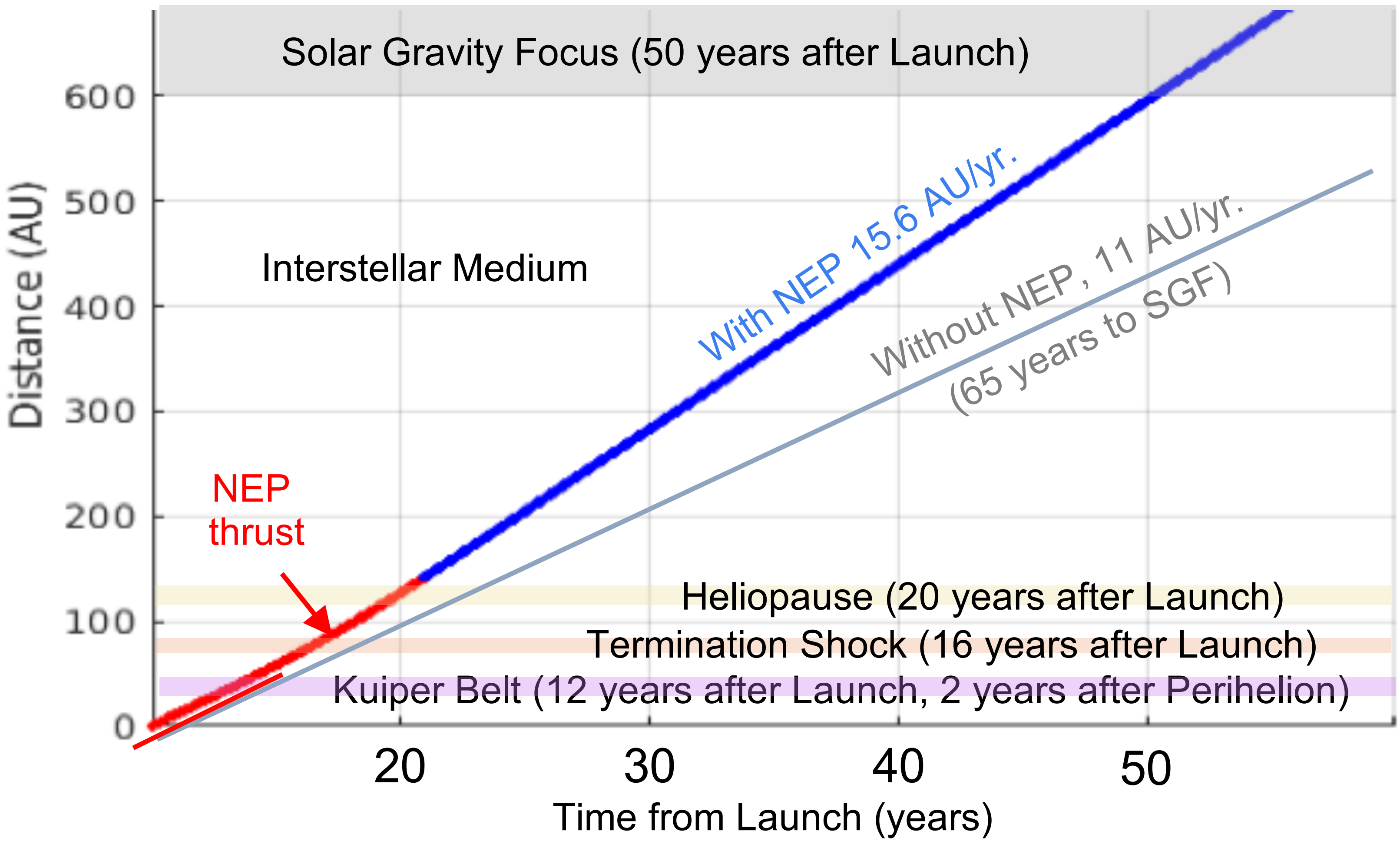




Large ISM Spacecraft:
3,000 kg dry mass
1,000 kg Sun shield
2,600 kg Xe propellant
1 m telescope w/ coronagraph
~100 kg additional instruments
10 kWe Kilopower reactor
NEXT thrusters

* Alkali et al. "Rapid Access to the Interstellar Medium using Solar Thermal Propulsion: A Feasibility Study" *JPL White Paper to be released September 2019*

ISM / SGLF Mission Example



Assumptions

- A 10k We fission power source would be developed for human sustainability on the moon and Mars sustainability.
- The nuclear and safety requirements for surface power would suffice for NEP without need for reengineering; although still required for the mechanical design.
- Sustainability (~10 kWe per astronaut, i.e. 5 modules per site plus more for expansion) would require a sustained product line.
- The surface power product line can be the source of a low-risk, low-cost power supply option for NEP, implying New Frontier class cost for Flagship class missions
- 10 kWe nuclear power source schedule would not likely support 2024 Artemis plan meaning 2028 will be likely 1st use
- The performance numbers used in the study conform to GRC and JPL practices for proposal work and should be conservative. Going forward, a more detailed engineering study should be performed.

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Conclusions

- A 10k We NEP capability would
  - Enable a new class of outer solar system missions that would not otherwise be possible.
  - Significantly enhance a range of other deep-space mission concepts, including ISM, by increasing science payload mass, reducing flight time, increasing mission lifetime, and providing ample power for science instruments and/or increased data rates.
- This capability represents a break-through enabling NASA to plan for large strategic missions to the outer solar system as recommended by the Space Studies Board in its report *Powering Science: NASA's Large Strategic Science Missions*.
- KRUSTY validated all of the Kilopower nuclear design goals and objectives, including the claim that future instantiations of the Kilopower design would not require full power nuclear testing, i.e., nuclear validation requires only zero power critical testing.

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